Exploring the Effects of Multiple Management Objectives and Exotic Species on Great Lakes Food Webs and Contaminant Dynamics

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ABSTRACT / A simulation model was developed to describe linkages among fish food web, nutrient cycling, and contaminant processes in the southern basin of Lake Michigan. The model was used to examine possible effects of management actions and an exotic zooplankter (*Bythotrephes*) on Lake Michigan food web and contaminant dynamics. The model predicts that contaminant concentrations in salmonines will decrease by nearly 20% if *Bythotrephes* successfully establishes itself in the lake. The model suggests that this decrease will result from lowered transfer efficiencies within the food web and increased flux of contaminants to the hypolimnion. The model also indicates that phosphorus management will have little effect on contaminant concentrations in salmonines. The modeling exercise helped identify weaknesses in the data base (e.g., incomplete information on contaminant loadings and on the biomass, production, and ecological efficiencies of dominant organisms) that should be corrected in order to make reliable management decisions.

The Great Lakes are exceptional among large lakes of the world in the degree to which fish population dynamics and water quality are being influenced by management actions at both the bottom (e.g., nutrient load reductions) and the top of the food web (fish stocking and harvesting and control of the parasitic sea lamprey). For instance, top-down control of Lake Michigan's summer epilimnetic plankton and water quality dynamics by alewife is possible (Scavia and others 1986), because the dynamics of alewife are influenced significantly by predation by stocked salmonines. A model developed by Scavia and others (1988) indicated that decreased zooplanktivory resulting from the decline in alewives led to changes in zooplankton and phytoplankton populations. These changes, in turn, led to altered mineral cycling and sedimentation that brought about a decrease in phosphorus concentrations. Instead of the bottom-up influence of phosphorus load reductions, these cascading food web effects were suggested by Scavia and others (1988) to be the major cause of observed improvements in phosphorus concentrations. Other examples of cascading food web effects are provided by Carpenter and Kitchell (1988).

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Great Lakes fish populations and water quality are also affected by toxic contaminant loads and events beyond the control of management, such as short term weather events (Rodgers and Salisbury 1981) and long-term climatic changes, exotic species invasions (e.g., by alewife and *Bythotrephes*), and evolutionary changes of existing species. Because fisheries-based revenues to the Great Lakes region alone are large (2.3–4.3 billion dollars per year; Talhelm 1988), a quantitative method is needed to understand and predict the relative importance of management and nonmanagement actions on fish populations and water quality. A corollary need is that the natural variability of fish populations and water quality must be estimated so that it can be determined if, and to what extent, management and nonmanagement actions will lead to statistically distinguishable changes in water quality and fish populations. The goal of this article, then, is to initiate development of a conceptual and mathematical modeling approach towards understanding and predicting Great Lakes food web and contaminant dynamics as affected by management actions and nature.

Multiple Management Goals for the Great Lakes Ecosystem

Often mentioned objectives of Great Lakes food web and water quality management are:

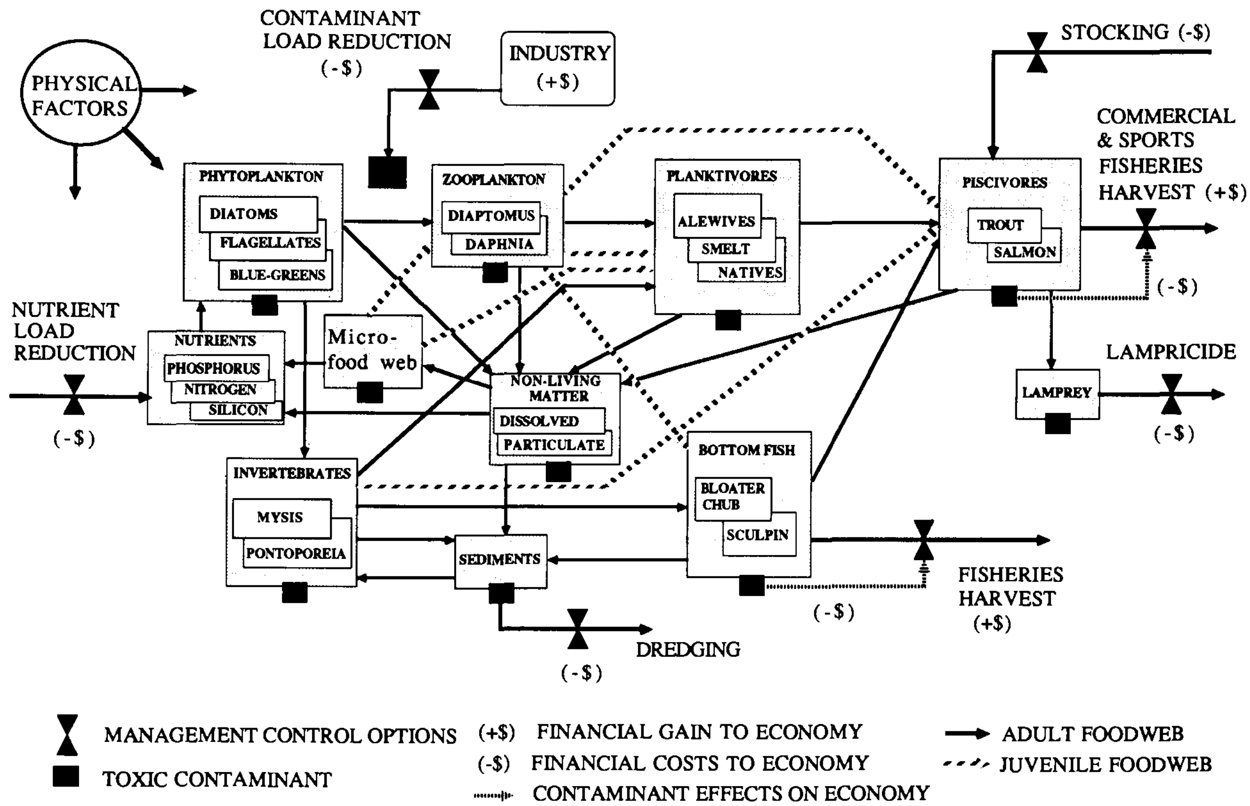

Figure 1. Conceptual diagram of major food web and contaminant processes in southern Lake Michigan (>100-m-depth contour only). Bowtie symbols indicate management options. Note that there is a financial cost associated with each management action. In most cases, there is also a financial cost associated with not managing. For instance, elimination of lamprey controls would adversely affect the multibillion dollar sports fishing industry. If management actions in the Great Lakes are not independent, then implementing one action will affect the costs of other actions. As cost minimization is a goal of managers, potential management synergisms should be understood and used advantageously.

1. Development of a trophy-sized sports fishery (Kitchell and Hewett 1987).
2. Reduction of basin-specific total phosphorus concentrations to those specified in the United States and Canada 1978 Water Quality Agreement (International Joint Commission 1978).
3. Reduction of contaminant concentrations in fish, water, and sediments to safe levels (International Joint Commission 1978).

Managers can pursue these food web and water quality objectives in southern Lake Michigan by exerting efforts at certain control points (Figure 1, bowtie symbols). Exercising one management option may unexpectedly affect the efficacy of another management option, however. For example, improved regulation of pollution inputs has improved water quality so that it is now possible for sea lampreys to spawn in areas that they previously could not (Moore and Lychwick 1980, J. Heinrick, US Fish and Wildlife Service, Marquette, Michigan, personal communication). Unfortunately, some of the additional spawning will be difficult to control through conventional means, especially in areas such as the St. Marys River. This raises the concern that lamprey attacks on desirable sports fish will increase.

A Model of Food Web and Water Quality Dynamics

The diagram in Figure 1 represents the conceptual framework from which a mathematical model was developed to describe causal relationships among food web, nutrient cycling, and contaminant processes at the >100-m-depth contour in the southern basin of Lake Michigan. The mathematical model was used to examine the hypothesis that one management action might affect the anticipated outcome of another management action. We further used the model to examine the hypothesis that successful establishment of the exotic zooplankton species *Bythotrephes* in the southern basin of

Lake Michigan will lead to a change in the contaminant concentration of top carnivore salmonines.

Model Description, Assumptions, and Limitations

Our model is an enhancement of an earlier model by Scavia and others (1988) that was used to examine how nutrient loading, competition, and predation affect the dynamics of phytoplankton and zooplankton in southern Lake Michigan. Using a bioenergetics approach, we added the biomass dynamics of aggregated alewife and aggregated salmonine populations. Average population parameters for the model were derived from Hewett and Stewart (1989), Stewart and Binkowski (1986) and Stewart and others (1981, 1983). Because alewife and salmonine populations are treated as aggregates, this initial model framework cannot be used to examine the effects of age-class specific stocking and harvesting strategies on food web and contaminant dynamics. Bloater (a bottom fish) and *Mysis* (an invertebrate) are also included in the model, but at this time are represented as constant biomass storages available for consumption by salmonines and alewives, respectively. Dynamic representation of bloaters and *Mysis* awaits development of bioenergetic models for them and improved definition of their role in the food web. Development of these models should improve our understanding of the dynamics of material fluxes between the pelagic and benthic zones and the importance of these materials to benthic food webs.

Pathways describing the behavior of a persistent contaminant in the food web were incorporated from Connolly and Thomann (1985) into the model. Processes included were contaminant uptake, depuration, trophic level transfers through consumption, and sorption reactions with living and nonliving particles. Unlike other models, the ecosystem and contaminant dynamics of this model are coupled, so as the ecosystem changes, the availability of living and nonliving adsorptive surfaces also changes. Coupled ecosystem–contaminant pathways that remain to be defined include contaminant dynamics of benthic invertebrates and bottom fish, and resuspension and biological–chemical dynamics of settled, particle-associated contaminants.

Simulation Conditions

The model was initialized with data representative of mid-1970s nutrient and plankton conditions. Nonfish coefficients and initial conditions were as described by Scavia and others (1988). Because estimates of Great Lakes fish biomass range widely, a matrix of possible mid-1970s alewife and salmonine biomass values (both lakewide and average individual weights) was initially used in the model to determine a combination that would reproduce observed plankton and nutrient dynamics at the >100-m-depth contour. The fish biomass estimates that produced the best match of model and data (according to criteria specified in Scavia and others 1988) were 15,000 metric tons (MT) of lakewide alewife and 10,000 MT of salmonine biomass, respectively. The most realistic simulations resulted from average initial wet weights of alewives and salmonine at 7 g and 454 g, respectively. Therefore, these lakewide and individual fish biomass values were used in all subsequent simulation experiments.

To examine effects of interactions among management and nonmanagement actions, the model was run with a variety of phosphorus loading, lamprey control, and *Bythotrephes* initial conditions. In all simulations, a persistent, nondegrading, highly partitioned ($k = 2 \times 10^5$) contaminant was loaded to a contaminant-free system at a hypothetical, steady rate of 1 unit/m^3/day to determine how contaminant concentrations in salmonines would be affected by management and nonmanagement actions. Phosphorus was input at 3 levels (0.0055, 0.0035, 0.0015 μg P/liter/day) to simulate the effects of less restrictive, present, or more stringent phosphorus loads to the lake. Lamprey control was set as either present or absent by increasing salmonine mortality by an additional 12.7% per day (estimated from Carlander 1969) when absent. *Bythotrephes* was programmed as either initially present (0.005 mg C/liter) or absent; coefficients governing the bioenergetics and predator–prey interactions of *Bythotrephes* were set according to Scavia and others (1988). If present, *Bythotrephes* was programmed to either strongly prefer *Daphnia* over *Diaptomous* or to show equal preference for both prey. Preliminary data suggest that the former case is believed to be the most plausible (H. A. Vanderploeg unpublished data). *Bythotrephes* was assumed to be a preferred prey item for alewife. All told, 18 different simulation conditions were evaluated and together represent a limited sensitivity analysis of the model.

Results and Discussion

Under all simulation conditions, predation pressure on alewives by salmonines caused alewife biomass at the >100-m-depth contour to decline from an initial 15,000 MT to about 3000 MT. Declines in alewife biomass due to predation brought about changes in phytoplankton and zooplankton composition, dissolved phosphorus concentrations, etc., similar to those described in Figures 3–7 of Scavia and others (1988). As alewife biomass declined, salmonine biomass decreased, leveled, or increased in direct relationship to the preference factor set for salmonines feeding on bloater. Determination of this preference factor is, therefore, central to our ability to adequately forecast salmonine biomass (and their

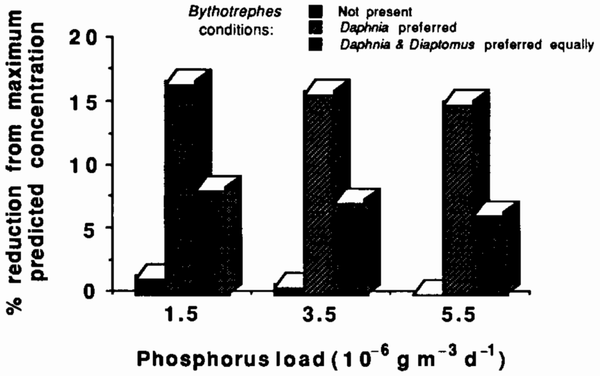

Figure 2. Predicted differences in salmonine contaminant concentrations under three phosphorus loads and three conditions of the exotic zooplankter *Bythotrephes*. Note that the ordinate is expressed as percent reduction from maximum simulated contaminant concentration.

contaminant concentrations) if the predicted decline in alewife occurs. If the major percentage of salmonine diets shift from alewife to other species, and if salmonine feeding rates remain the same as before the decline in alewife, it is these other species that will primarily dictate future salmonine biomass and contaminant dynamics. Because there is considerable uncertainty about how salmonines would adapt to low alewife availability, the results that follow correspond to the point in time at which salmonines are at their peak biomass, just before the decline in alewives.

Effects of *Bythotrephes*

The model was used to explore the effect of the presence (two feeding preference scenarios as in Scavia and others 1988) or absence of the exotic zooplankter *Bythotrephes* on salmonine contaminant concentration. Consistent with our hypothesis was the model prediction that successful establishment of *Bythotrephes* could alter salmonine contaminant concentrations (Figure 2). Greatest reductions (17%) were predicted when *Bythotrephes* preferentially fed on *Daphnia* over *Diaptomous*, the scenario thought to be most likely. If *Bythotrephes* preferred *Daphnia* and *Diaptomous* equally, predicted reductions in salmonine contaminant concentrations were about 8%. These predicted changes in salmonine contaminant concentration represent a field-testable hypothesis.

Why did salmonine contaminant concentrations decrease when *Bythotrephes* were present in the model? The model indicates that *Bythotrephes* will decrease the rate of contaminant transfer to alewife, the preferred food source of salmonines, primarily by affecting *Daphnia* dynamics. Simulated changes in *Daphnia* biomass dynamics affected algal and particle dynamics, as in Scavia and others (1988). These changes in food web and particle dynamics affect the amount of contaminant that can reach the simulated alewife population. *Bythotrephes* directly competes with alewife for *Daphnia* biomass, and thereby reduces alewife consumption of *Daphnia*-associated contaminants. Although alewife consume the *Bythotrephes* that feed on *Daphnia*, the alewife do not receive the same contaminant flux from them that they would have from direct consumption of *Daphnia*. The flux is decreased because *Bythotrephes* represents an additional trophic level with associated energy losses in the food chain leading to alewives. *Bythotrephes* do not assimilate all of the *Daphnia*'s biomass and associated contaminants; the unassimilated portion becomes particulate organic carbon, unavailable for alewife consumption.

A secondary effect of *Bythotrephes* on ecosystem contaminant dynamics is suggested by the model. In simulations with *Bythotrephes*, *Daphnia* biomass is suppressed because total predation pressure on *Daphnia* increases due to the presence of two predators (*Bythotrephes* and alewife) instead of one. The decrease in *Daphnia* biomass leads to an increase in the biomass of their major food source, green and blue–green algae. As a result, the flux of sinking algal biomass and associated contaminants to hypolimnetic sediments increases. This model prediction represents another field-testable hypothesis. Unfortunately, the model is not at the stage of development where the subsequent fate of the increased contaminant flux to the sediments can be predicted. It is likely that most of this increased contaminant flux would eventually reside in benthic invertebrates and bottom-feeding fish. If so, it could become available to salmonines if they shift their diets from alewife to bloaters as alewives decline.

Effects of Management Actions

We hypothesized that the effects of one management option may unexpectedly affect the efficacy of another management option. This hypothesis was examined by determining the effects of three phosphorus load scenarios and the presence or absence of lamprey control on salmonine contaminant concentrations. The model predicted that control of phosphorus loads and lamprey would have little effect on salmonine contaminant concentrations. Only a 1% change in salmonine contaminant concentration was predicted when present phosphorus loads were sizably increased or decreased (Figure 2). Eliminating lamprey control led to a 5% decrease in peak salmonine biomass and a small increase (<1%) in salmonine contaminant concentrations.

Therefore, over the simulation period from initial conditions to peak salmonine biomass, the model indicates that the effects of phosphorus and lamprey management on salmonine contaminants will be small in comparison to the simulated effects of *Bythotrephes*.

Looking Forward

Improved predictions from this model of southern Lake Michigan contaminant and ecosystem dynamics depends on improved understanding of pelagic–benthic carbon, nutrient, and contaminant coupling. Understanding the role of lipids in food web bioenergetics and contaminant transfer from prey to predator appears crucial. In addition, better estimates of fish population biomass and age structure are needed to simulate more adequately fish population bioenergetics and food web dynamics. Presently, however, short-term simulations suggest that the successful establishment of an exotic zooplankton species might cause more noticeable changes in food web and water quality characteristics than the effects of some management actions. By using models, we may transform some potentially surprising ecological changes into anticipated events.

Enhanced monitoring is needed to quantify the natural variability of Great Lakes water quality constituents (e.g., phosphorus, PCBs, etc.) and the biomass, quantity, and characteristics of Great Lakes organisms. Without this information, it will be difficult to discern whether management activities actually affect the system. As demonstrated by Bartell and others (1983) and Fontaine and Lesht (1987), probabilistic models can be used to predict statistical distributions of ecological state variables (e.g., numbers, biomass, and age-class distributions of organisms, etc.), and ecological processes (e.g., production, nutrient cycling, etc.). Given the ability to predict or measure these statistical distributions for baseline conditions, ecosystem managers should use models to guide them to management techniques that will produce results that are statistically distinguishable from the baseline variability of the systems components. In other words, why spend money trying to manage a system if an effect cannot be clearly demonstrated?

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